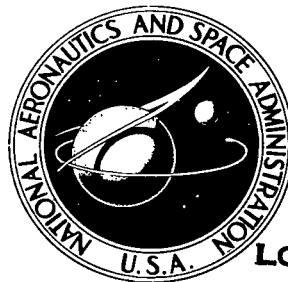


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# EXPERIMENTAL AND PREDICTED CAVITATION PERFORMANCE OF 80.6° HELICAL INDUCER IN HIGH-TEMPERATURE WATER

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16. Abstract The cavitating performance of a stainless steel 80.6° flat-plate helical inducer was investigated in water over a range of liquid temperatures and flow coefficients. A semi-empirical prediction method was used to compare predicted values of required net positive suction head in water with experimental values obtained in water. Good agreement was obtained between predicted and experimental data in water. The required net positive suction head in water decreased with increasing temperature and increased with flow coefficient, similar to that observed for a like inducer in liquid hydrogen.					
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# EXPERIMENTAL AND PREDICTED CAVITATION PERFORMANCE OF 80.6° HELICAL INDUCER IN HIGH-TEMPERATURE WATER

by George Kovich  
Lewis Research Center

## SUMMARY

The cavitating performance of a stainless steel 80.6° flat-plate helical inducer is evaluated in water at a rotative speed of 15 000 rpm. The net positive suction head (NPSH) requirements were determined over a range of water temperature from 308.2 to 470.4 K (554.7° to 864.7° R) and a flow coefficient range of 0.100 to 0.120. A semi-empirical prediction method is used to compare predicted values of NPSH in water with experimental values over the temperature and flow coefficient range. The experimental cavitation performance of the stainless steel inducer is compared in water at room temperature with that of a same design aluminum inducer which had also been operated in liquid hydrogen. Some differences existed between the predicted cavitation performance of the stainless steel inducer and the aluminum inducer measured in liquid hydrogen. It is believed that the cavitation regions in these inducers were not similar.

Comparison of experimental NPSH requirements in water with predicted NPSH was good. The required NPSH in water decreased with increasing temperature and increased with increasing flow coefficient, similar to that observed for liquid hydrogen. The non-cavitating performance of the inducer was unaffected by water temperature.

## INTRODUCTION

The cavitation performance of an inducer operated in cryogenic rocket propellants such as liquid hydrogen is affected by flow conditions, heat transfer, and thermodynamic properties of the fluid. These combined effects on cavitation performance, referred to as the thermodynamic effects of cavitation, are discussed in detail in reference 1. Substantial improvements in the cavitation performance over that for cold water have been obtained for inducers operated in liquid hydrogen at temperatures above 13.9 K (25° R) as a result of the thermodynamic effects of cavitation (refs. 2 and 3).

Thermodynamic effects of cavitation are negligible in room temperature water; however, at higher temperatures above say 366.5 (660° R), water exhibits measurable thermodynamic effects of cavitation with trends similar to those of liquid hydrogen (ref. 4).

The advantages of using water in place of liquid hydrogen in experimental research and development testing of rocket engine pumps and inducers include a potential savings in cost of fabrication as well as in the operation of test facilities. It is therefore desirable to evaluate the feasibility of such a test procedure by comparing the performance of inducers in high temperature water with that obtained in liquid hydrogen.

A semi-empirical method of predicting the thermodynamic effects of cavitation developed from Venturi cavitation studies (ref. 5) has been used to correlate the cavitation performance of an inducer in one liquid with that in another fluid (ref. 4). This prediction method has been used to predict the cavitation performance of several inducers and pumps handling various liquids over a range of liquid temperatures and rotative speeds.

In a previous investigation (ref. 6), the cavitation performance of an 84° helical inducer in high temperature water was compared with that of a similar inducer in liquid hydrogen (ref. 3). Cavitation performance in hydrogen, predicted from water data, was shown to be in reasonable agreement with the experimental performance of the hydrogen inducer.

The object of this investigation is to determine the cavitation performance of an 80.6° helical inducer in high temperature water and to evaluate the degree to which water performance data could be used to predict the performance in hydrogen of a similar inducer. In the present study, the cavitation performance of the 80.6° flat-plate helical inducer was evaluated in water over a temperature range of 308.2 to 480.4 K (554.7° to 864.7° R). The required net positive suction head (NPSH) was measured for three nominal flow coefficients at a rotative speed of 15 000 rpm and for one nominal flow coefficient of 10 000 rpm.

The cavitation performance in room temperature water was also obtained for an aluminum 80.6° inducer of the same design at a rotative speed of 10 000 rpm. The performance of this inducer had been obtained in liquid hydrogen (ref. 7). This investigation was conducted at the Lewis Research Center.

## APPARATUS AND PROCEDURE

### Test Inducer

The test inducer was a three-bladed, constant lead helical inducer with a tip angle of 80.6°. It was machined from 400 series stainless steel with a constant tip diameter of 12.639 centimeters (4.976 in.) and a hub to tip ratio of about 0.5. The detailed geometric features and a photograph of the inducer are shown in figure 1. A photograph and

geometric details of the like design aluminum inducer operated in liquid hydrogen are shown in reference 7. The leading edges of both inducers were faired on the suction surface only.

## Test Facility

The investigation was conducted using the Lewis high temperature water tunnel, a closed-loop pump test facility. The system is described in detail in reference 8. A schematic diagram of the loop is shown in figure 2 and a photograph of the facility is shown in figure 3. For test operations the loop is filled with demineralized water after which the gas content of the water is reduced to less than 3 parts per million by weight in an auxiliary degasifying system. Solid matter 5 microns or larger are removed by filtering during the degasifying process. The water is then heated to the desired temperature in the cross-flow heat exchanger which forms a bypass leg around the flow control valve.

## Instrumentation and Procedure

Overall performance of the inducer was obtained by measuring flow conditions in the inlet line approximately 91.4 centimeters (36 in.) ahead of the inducer blade leading edge and 2.5 centimeters (1 in.) downstream of the blade trailing edge. Four manifolded pipe wall static taps and a closed-end calibrated copper-constantan thermocouple at midstream were located at the inlet measuring station. One shielded total pressure probe at midblade height was located at the outlet station. Flow rate was measured with a Venturi meter. Pressure measurements were taken with calibrated strain-gage differential pressure transducers. Rotative speed was obtained with a electronic frequency counter in conjunction with a magnetic pickup. All data were recorded by an automatic digital potentiometer.

The estimated maximum measurement errors due to instrumentation for the minimum and maximum water temperatures are presented in the following table: (Measurement errors at the intermediate water temperatures vary linearly between the given values.)

Parameter	Water temperature limit, K ( $^{\circ}$ R)	
	308.2 (554.7)	480.4 (864.7)
	Error	
1. Inlet total head, m (ft)	$\pm 0.2$ ( $\pm 0.5$ )	$\pm 0.6$ ( $\pm 2$ )
2. Net positive suction head, m (ft)	$\pm 0.2$ ( $\pm 0.5$ )	$\pm 1.5$ ( $\pm 1.5$ )
3. Head-rise across inducer, m (ft)	$\pm 0.3$ ( $\pm 1.0$ )	0.3 ( $\pm 1$ )
4. Rotor speed, rpm	$\pm 30$	$\pm 30$
5. Temperature, K ( $^{\circ}$ R)	0.28 ( $\pm 0.5$ )	0.28 ( $\pm 0.5$ )
6. Venturi flow, percent	$\pm 0.5$	$\pm 0.5$

Test operations were conducted at rotative speeds of 15 000 and 10 000 rpm at five nominal water temperatures of 308.2, 394.3, 422.1, 449.9, and 477.6 K (554.7 $^{\circ}$ , 709.7 $^{\circ}$ , 759.7 $^{\circ}$ , 809.7 $^{\circ}$ , and 859.7 $^{\circ}$  R). The required NPSH was obtained for the nominal flow coefficients of 0.100, 0.110, and 0.120 at 15 000 rpm and 0.110 at 10 000 rpm. Cavitating performance was obtained by holding the flow coefficient  $\phi$  constant while reducing the inlet pressure (NPSH) until the inducer head-rise coefficient  $\psi$  deteriorated to less than 70 percent of the noncavitating value. The noncavitating performance was obtained at a sufficiently high value of inducer inlet pressure (NPSH) to insure that cavitation had no effect on the inducer performance while the flow coefficient was reduced. Vapor pressure corresponds to the measured water temperature at the inlet station. The NPSH is determined as the difference between inducer inlet total head and the inlet water vapor head.

Cavitation performance for the aluminum 80.6 $^{\circ}$  inducer which had been operated in liquid hydrogen (ref. 7) was obtained in room temperature water for the three nominal flow coefficients at 10 000 rpm.

## RESULTS AND DISCUSSION

### Noncavitation Performance

The noncavitation performance is defined as that which shows no measurable change in inducer head-rise as the NPSH is either increased or decreased at a constant flow coefficient. The noncavitating head-rise coefficient for the 80.6 $^{\circ}$  helical inducer as a function of flow coefficient for several water temperatures is shown in figure 4. The noncavitation performance is unaffected by changes in water temperature over the range of flow coefficients.

## Cavitation Performance

The head-rise coefficient ratio  $\psi/\psi_{nc}$  as a function of NPSH at several water temperatures is presented in figure 5 for three nominal flow coefficients at a rotative speed of 15 000 rpm and in figure 6 for one nominal flow coefficient at 10 000 rpm. The vertical dashed lines represent the points at which the value of NPSH equals the velocity head  $V_1^2/2g$  at the inducer inlet. At these values of NPSH the local stream static pressure equals the vapor pressure of the water. Any further reduction in NPSH causes boiling in the inducer inlet line and the resultant vapor is ingested by the inducer.

As the water temperature is increased, the required NPSH is decreased. As the flow coefficient is increased for a given liquid temperature and performance level, the required NPSH increases. The data of figures 5 and 6 show that the inducer is capable of delivering a useful head rise while operating with vapor ingestion at temperatures above 450 K (810° R). For a given liquid temperature, the required NPSH was higher for 15 000 rpm than for 10 000 rpm.

The required NPSH for a head-rise coefficient ratio  $\psi/\psi_{nc}$  of 0.7 is shown in figure 7 as a function of flow coefficient  $\phi$  for several water temperatures and a rotative speed of 15 000 rpm. Values of NPSH less than the inlet line velocity head  $V_1^2/2g$  are indicated by the shaded area on this figure. Data in the shaded area indicate that the inducer can operate at a head-rise coefficient ratio  $\psi/\psi_{nc}$  of 0.7 with vapor in the inlet line. The thermodynamic effects of cavitation or changes in required NPSH are larger at the lower flow coefficients. The data in figure 7 also indicate, as did the data in figure 5, that the required NPSH increases with increasing flow coefficient for a constant liquid temperature; and the required NPSH is substantially reduced for a constant flow coefficient as the liquid temperature is increased.

## Predicting Thermodynamic Effects of Cavitation

A method for predicting the thermodynamic effects of cavitation and the cavitation performance of inducers is presented in detail in reference 4. The method is briefly reviewed before presenting the comparison of predicted and experimental cavitation performance.

A heat balance between the heat required for vaporization and that drawn from the liquid adjacent to the cavity is used to obtain  $\Delta h_v$ , the cavity pressure depression below free stream vapor pressure

$$\Delta h_v = \left(\frac{\rho_v}{\rho_l}\right) \left(\frac{L}{C_p}\right) \left(\frac{dH_{vp}}{dT}\right) \left(\frac{\gamma_v}{\gamma_l}\right) \quad (1)$$

With known properties of the fluid, values of  $\Delta h_v$  as a function of vapor to liquid volume ratio  $\gamma_v/\gamma_l$  can be obtained by a numerical integration of equation (1) which accounts for changes in fluid properties as the equilibrium temperature decreases due to the evaporative cooling (ref. 4). The calculated depressions in vapor pressure  $\Delta h_v$  are plotted as a function of vapor to liquid volume ratio  $\gamma_v/\gamma_l$  for a range of temperatures for water in figure 8.

The absolute value of  $\gamma_v/\gamma_l$  for a particular inducer cannot be experimentally determined. However, it is shown in reference 4 that, if a reference value of  $\gamma_v/\gamma_l$  is established experimentally by estimating  $\Delta h_v$ , values of  $\gamma_v/\gamma_l$  relative to this reference value can be estimated from the following equation:

$$\frac{\gamma_v}{\gamma_l} = \left( \frac{\gamma_v}{\gamma_l} \right)_{\text{ref}} \left( \frac{\alpha_{\text{ref}}}{\alpha} \right) \left( \frac{N}{N_{\text{ref}}} \right)^{0.8} \quad (2)$$

Equation (2) requires geometrically similar cavitating flow conditions, that is, the same flow coefficient and the same head-rise coefficient ratio for the desired inducer operating condition as for the reference operating condition.

The inducer cavitation performance for a constant flow coefficient and head-rise coefficient ratio but with changes in liquid, liquid temperature, and/or rotative speed may be predicted with the following equation (ref. 4):

$$\frac{NPSH + \Delta h_v}{NPSH_{\text{ref}} + (\Delta h_v)_{\text{ref}}} = \left( \frac{N}{N_{\text{ref}}} \right)^2 \quad (3)$$

For a fixed rotative speed, equation (3) reduces to

$$NPSH_{\text{ref}} - NPSH = \Delta h_v - (\Delta h_v)_{\text{ref}} \quad (4)$$

which states that a change in NPSH requirements for an inducer in different liquids and/or liquid temperatures is equal to the change in cavity pressure depression  $\Delta h_v$ . The prediction method (ref. 4) requires that two experimental test points be available for the inducer of interest. These experimental data can be for any combination of liquid, liquid temperature, or rotative speed provided at least one set of data exhibits a measurable thermodynamic effect of cavitation. From these experimental data, the cavitation performance of that inducer can be predicted for any liquid, liquid temperature, or rotative speed.



## Comparison of Experimental and Predicted Water Performance

The comparison of experimental with predicted values of NPSH as a function of flow coefficient is shown in figure 9 for several water temperatures and a rotative speed of 15 000 rpm. Experimental data at water temperatures of 308.2 and 424.8 K (554.7° and 764.7° R) were arbitrarily chosen to establish reference values of  $\Delta h_v$  and  $\gamma_v/\gamma_l$  for a head-rise coefficient ratio of 0.7 at a number of flow coefficients. The solid symbols represent values obtained from a cross plot of the experimental data obtained for the other water temperatures. Good agreement between experimental and predicted values of NPSH is obtained for the values of NPSH greater than the inlet fluid velocity head  $V_1^2/2g$ . Predicted values of NPSH below the value of  $V_1^2/2g$  are not useful because similarity of the cavitated flow regions is not maintained when boiling occurs in the inducer inlet line. Experimental values of NPSH smaller than the inducer inlet velocity head cannot be used to establish reference values of  $\Delta h_v$  and  $\gamma_v/\gamma_l$  for the same reason.

A comparison of experimental and predicted values of NPSH for the inducer in water at 10 000 rpm and several temperatures is shown in the following table. The predicted performance is obtained with the reference values of  $\gamma_v/\gamma_l$  and  $\Delta h_v$  previously established at the rotative speed of 15 000 rpm for the head-rise coefficient ratio of 0.7.

Flow coefficient, $\phi$	Water temperature, T		Experimental NPSH		Predicted NPSH	
	K	°R	m	ft	m	ft
0.1090	308.2	554.7	8.5	26.0	8.6	26.1
.1104	395.9	712.7	7.8	23.7	7.8	23.7
.1120	424.8	764.7	4.9	15.0	5.5	16.7

Good agreement is obtained between the experimental and predicted values of NPSH for the change in rotative speed from 10 000 to 15 000 rpm. Stress limitations for operation of the rotor in water prevented obtaining data above 15 000 rpm to determine the extent of speed increase for which the prediction method would produce reliable results.

## Considerations of Geometric Similarity

As previously discussed, the prediction method (ref. 4) requires geometrically similar cavitating flow conditions; that is, similarity of the cavitated regions in the inducer at the desired operating condition and the reference operating condition. Therefore,

before any comparison of the predicted cavitation performance of one inducer can be made with the experimental performance of another inducer of the same design, it is necessary to show that geometric similarity of the cavitated regions in the two inducers does exist. A comparison of the cavitation performance of the two inducers at the same flow conditions and where the thermodynamic effects of cavitation are negligible could qualitatively establish this similarity. Agreement between the resulting curves of required NPSH as a function of flow coefficient for a given head-rise coefficient ratio would indicate that the vapor volumes for the two inducers are essentially the same for corresponding flow coefficients and that the inducers are in fact physically identical in design. If there are differences between the two curves, it would indicate that the cavitation vapor volumes in the two inducers are different. Small deviations in the sharpness or angle settings of the blade leading edges between the two inducers, for example, could cause such differences in cavitation performance.

In order to evaluate the similarity of the 80.6° aluminum inducer which was run in the tests in liquid hydrogen (ref. 7), and the stainless steel inducer used in the present investigation, the aluminum inducer was run in the high temperature water tunnel with room temperature water. The cavitation performance is compared to that of the stainless steel inducer with water at room temperature where the thermodynamic effects of cavitation are negligible. The required NPSH for the two inducers is compared in figure 10 for a  $\psi/\psi_{nc}$  of 0.7 and a rotative speed of 10 000 rpm. The performance of the steel inducer at 10 000 rpm was scaled from data obtained at 15 000 rpm. Stress limitations for the aluminum inducer precluded obtaining data in water above a rotative speed of 10 000 rpm and at water temperatures above 338.8 K (610° R).

The measured required NPSH for the aluminum inducer was nearly the same as that for the stainless steel inducer at a flow coefficient of 0.10, but was 1.8 meters (6 ft) higher at the flow coefficient of 0.12. The cavitation characteristics for the two inducers are apparently different at the higher flow coefficients; therefore, the method of reference 4 could not be used to predict the cavitation performance from one inducer to the other in any liquid. Close inspection of the leading edge fairings of the two inducers revealed small geometric differences which probably caused the differing cavitation performance.

It is concluded that it is highly desirable to use the same physical inducer or pump rotor in the two different media if cavitation performance is to be scaled from data obtained in the one media for comparison with that obtained in the other.

As an independent evaluation of the range of applicability of the prediction method, it should be possible to predict the cavitation performance of the aluminum inducer in liquid hydrogen at the triple point temperature (13.8 K or 24.9° R) from the measured performance in room temperature water using equation (3). For both of these conditions the thermodynamic effects of cavitation were negligible. The performance in water at a rotative speed of 10 000 rpm is scaled to compare with that in liquid hydrogen at

30 000 rpm. The aluminum inducer performance in liquid hydrogen at 13.8 K (24.9° R) is obtained using the prediction method and experimental data of reference 7 at temperatures of 17.2 and 18.9 K (31.0° and 34.1° R) and at a rotative speed of 30 000 rpm.

The results of the comparison are presented in figure 11. Although the agreement is good at a flow coefficient of 0.100, the value predicted from hydrogen data gives an NPSH 18.3 meters (60 ft) greater than that for water at a flow coefficient of 0.116. A number of factors may contribute to this difference. These would include mechanical distortion of the impeller which could be caused either by high speed in liquid hydrogen, or by high blade loadings in water. The effect of Reynolds number on cavitation performance could also be a factor.

A previous investigation of Reynolds number effects on the performance of an 80.6° helical inducer of like design in room temperature water indicated the occurrences of some changes in cavitation performance with rotative speed for a range of Reynolds number from  $1.85 \times 10^7$  to  $3.7 \times 10^7$  (ref. 9). Although no consistent trend was observed, it is easily possible that the sevenfold change in Reynolds number for the aluminum inducer, from  $2.8 \times 10^7$  in room temperature water at 10 000 rpm to  $19.5 \times 10^7$  in hydrogen at 30 000 rpm, could have had a substantial effect on the scaling of its cavitation performance.

Apparently the range of speed and change in fluid properties over which the scaling of cavitation performance was attempted for the aluminum inducer was too large for the attainment of reasonable accuracy.

## SUMMARY OF RESULTS

The cavitation performance for an 80.6° stainless steel helical inducer was measured in water at temperatures from 308.2 to 480.4 K (554.7° to 864.7° R). The required net positive suction head (NPSH) was measured for three nominal flow coefficients, 0.100, 0.110, and 0.120 at a rotative speed of 15 000 rpm and one nominal flow coefficient of 0.110 at 10 000 rpm. The experimental cavitation performance obtained in high temperature water was compared with predicted cavitation performance obtained using an available semi-empirical prediction method. The experimental cavitation performance of the stainless steel inducer and an aluminum inducer of the same design was compared in room temperature water. The aluminum inducer had also been operated in liquid hydrogen in another facility.

The following principal results were obtained:

1. The required NPSH in water decreased with increasing water temperature and increased with flow coefficient similar to that observed for the like aluminum inducer in liquid hydrogen.

2. The predicted and experimental values of NPSH for the stainless steel inducer in high temperature water were in good agreement.

3. The noncavitating performance of the stainless steel inducer was essentially independent of the water temperature.

4. Comparison of the experimental cavitation performance for both inducers in room temperature water indicated that the cavitated regions in the inducers were not similar at the same flow conditions. The dissimilarity of cavitation was probably caused by small differences in the geometry of the leading edge fairings. It is highly desirable to use the same physical inducer in such cavitation scaling investigations.

5. Cavitation performance for the aluminum inducer in room temperature water at 10 000 rpm could not be accurately scaled to that predicted from experimental data for the same inducer in liquid hydrogen at 30 000 rpm. Differences of predicted cavitation performance in liquid hydrogen were attributed to distortion of blade leading edge fairing geometry by high rotative speed or changes in hydrodynamic loading between the two liquids, and the effects of large changes in Reynolds number on cavitation performance.

Lewis Research Center,

National Aeronautics and Space Administration,

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764-74.

## APPENDIX - SYMBOLS

$C_p$	specific heat of liquid, J/(kg)(K); Btu/(lbm)(°R)
$g$	local acceleration due to gravity, 980 m/sec <sup>2</sup> ; 32.163 ft/sec <sup>2</sup>
$H_{vp}$	vapor pressure head, m; ft
$\Delta h_v$	cavity pressure drop below vapor pressure, m; ft
$L$	latent heat of vaporization, J/kg; Btu/lbm
$N$	rotational speed, rpm
$NPSH$	net positive suction head, m; ft
$T$	temperature, K; °R
$V_1$	inlet velocity, m/sec; ft/sec
$\gamma_v/\gamma_l$	vapor-volume to liquid-volume ratio
$\alpha$	thermal diffusivity, m <sup>2</sup> /hr; ft <sup>2</sup> /hr
$\rho_l$	liquid density, kg/cu m; lbm/cu ft
$\rho_v$	vapor density, kg/cu m; lbm/cu ft
$\phi$	flow coefficient
$\psi$	head-rise coefficient
$\psi_{nc}$	noncavitating head-rise coefficient
$\psi/\psi_{nc}$	ratio of cavitating to noncavitating head-rise coefficient
Subscript:	
ref	reference

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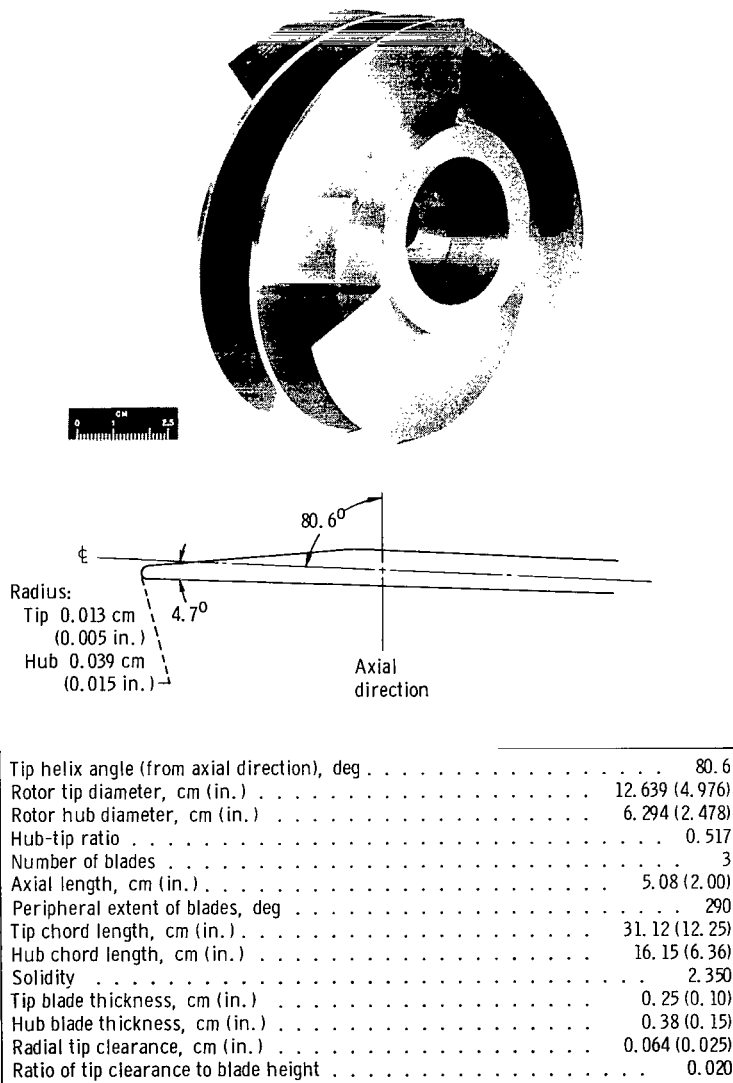


Figure 1. - Geometric details of 80.6° helical inducer.

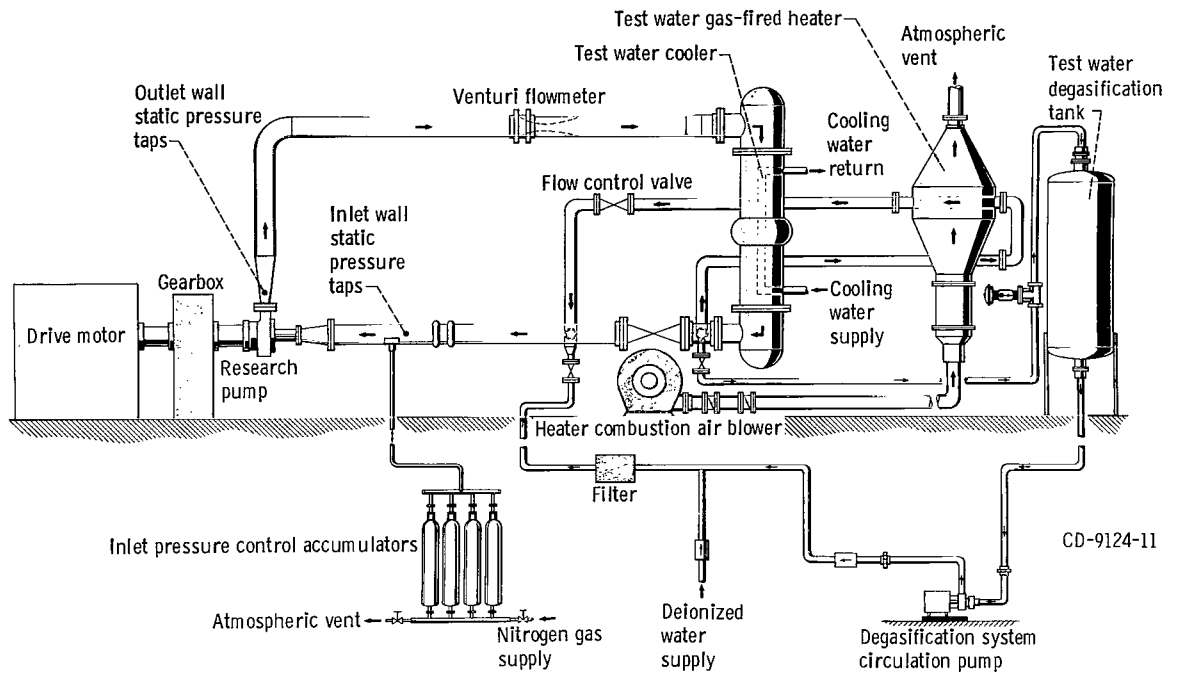


Figure 2. - Schematic of high-temperature water tunnel.

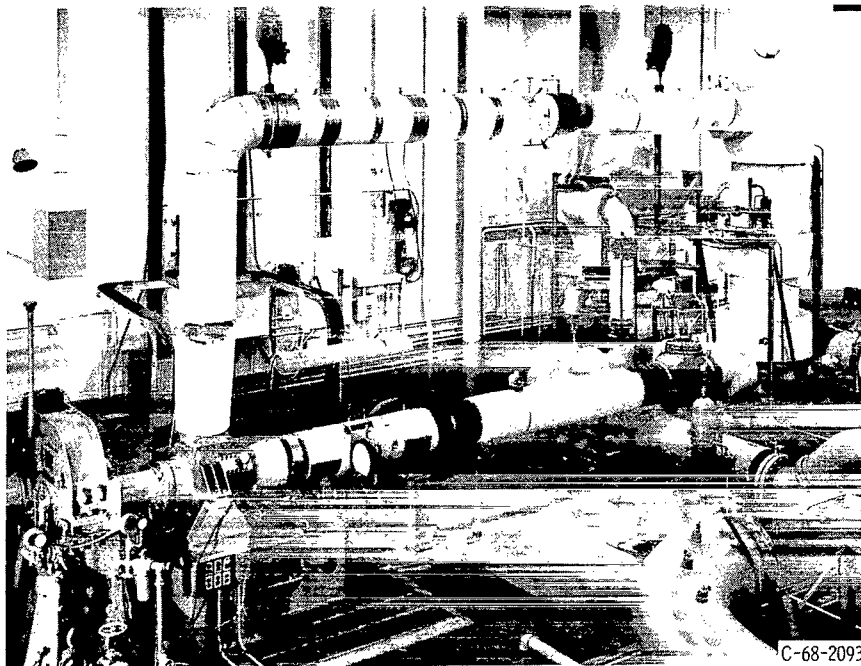


Figure 3. - High-temperature water tunnel.



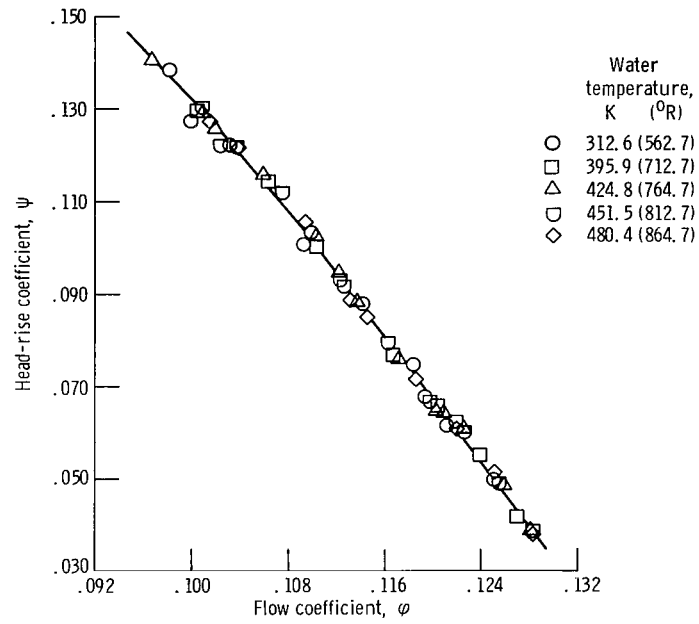


Figure 4. - Noncavitating performance of 80.6° helical inducer in water at rotative speed of 15 000 rpm and net positive suction head of 73.2 meters (240 ft).

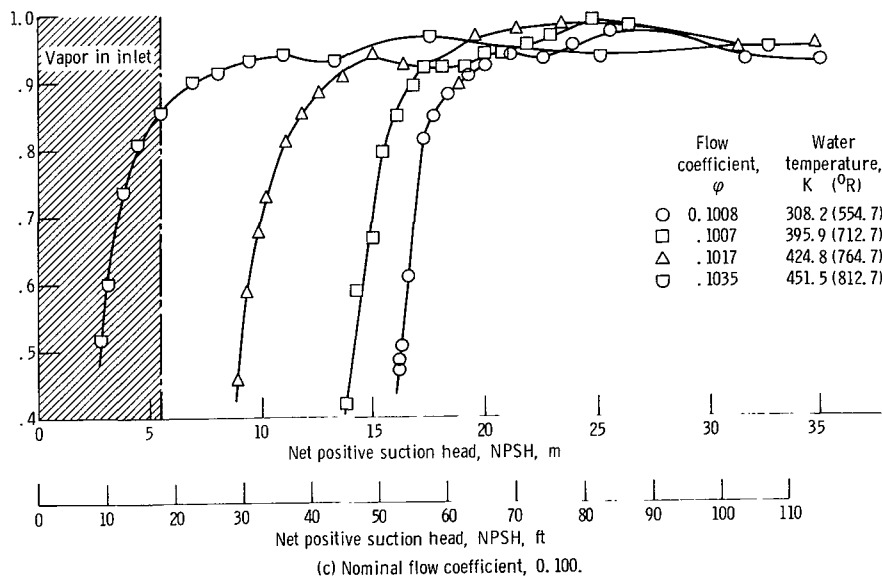
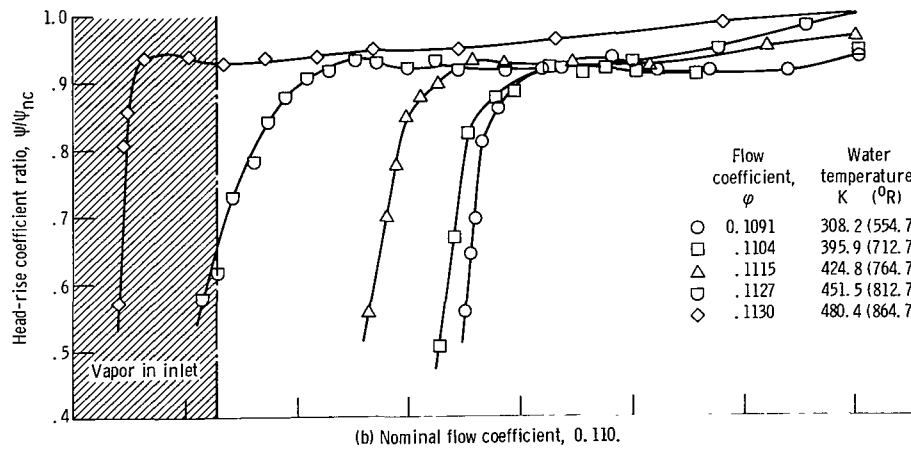
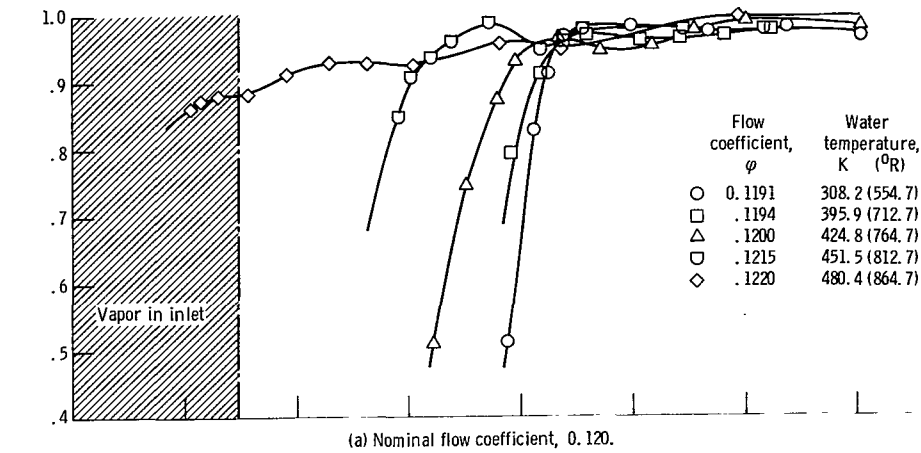


Figure 5. - Cavitating performance of 80.6° helical inducer in water at rotative speed of 15 000 rpm and several temperatures.

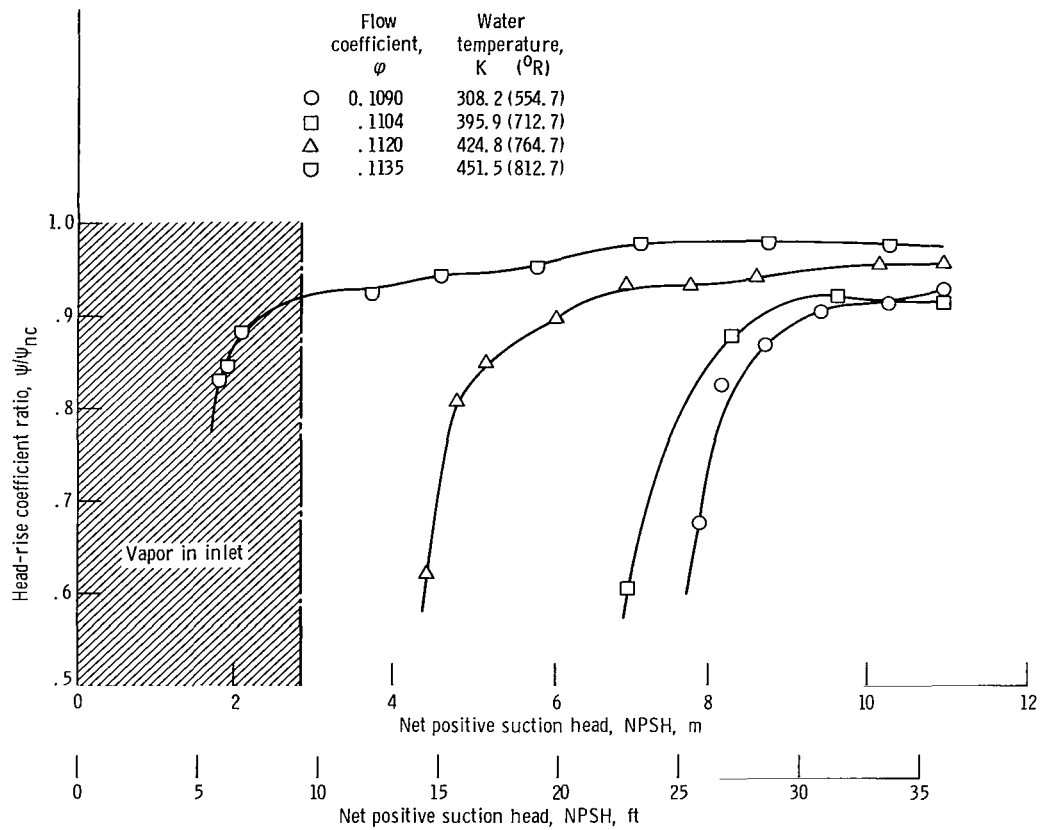


Figure 6. - Cavitation performance of 80.6° helical inducer in water at rotative speed of 10 000 rpm, several temperatures, and nominal flow coefficient of 0.110.

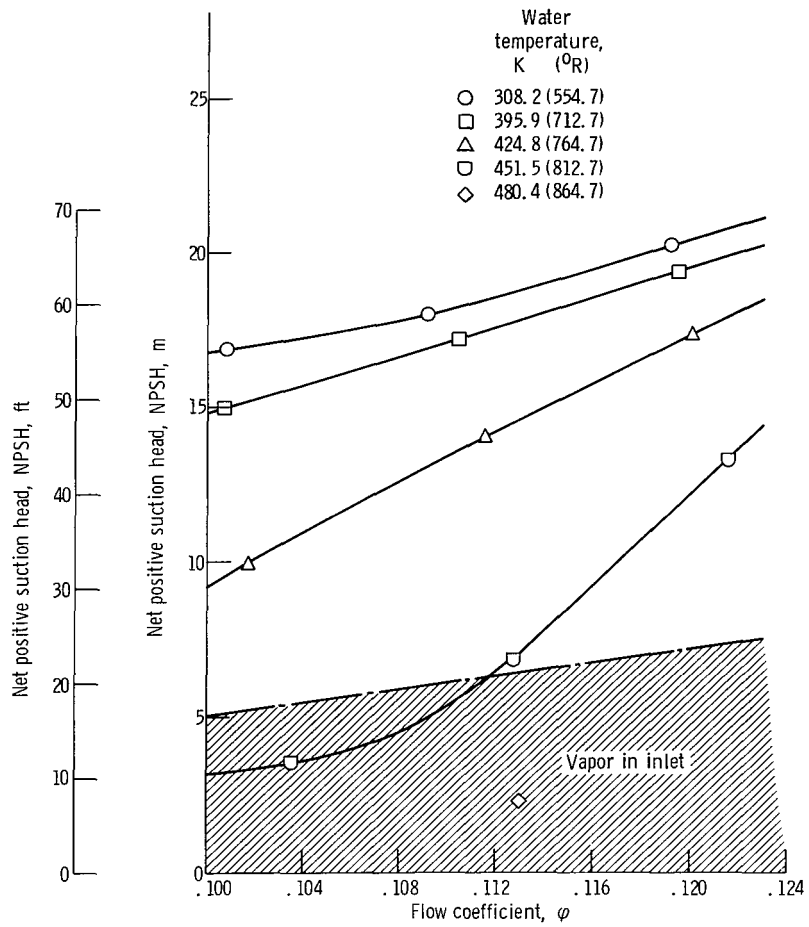


Figure 7. - Required net positive suction head for 80.6° helical inducer in water at head-rise coefficient ratio of 0.7 and rotative speed of 15 000 rpm.

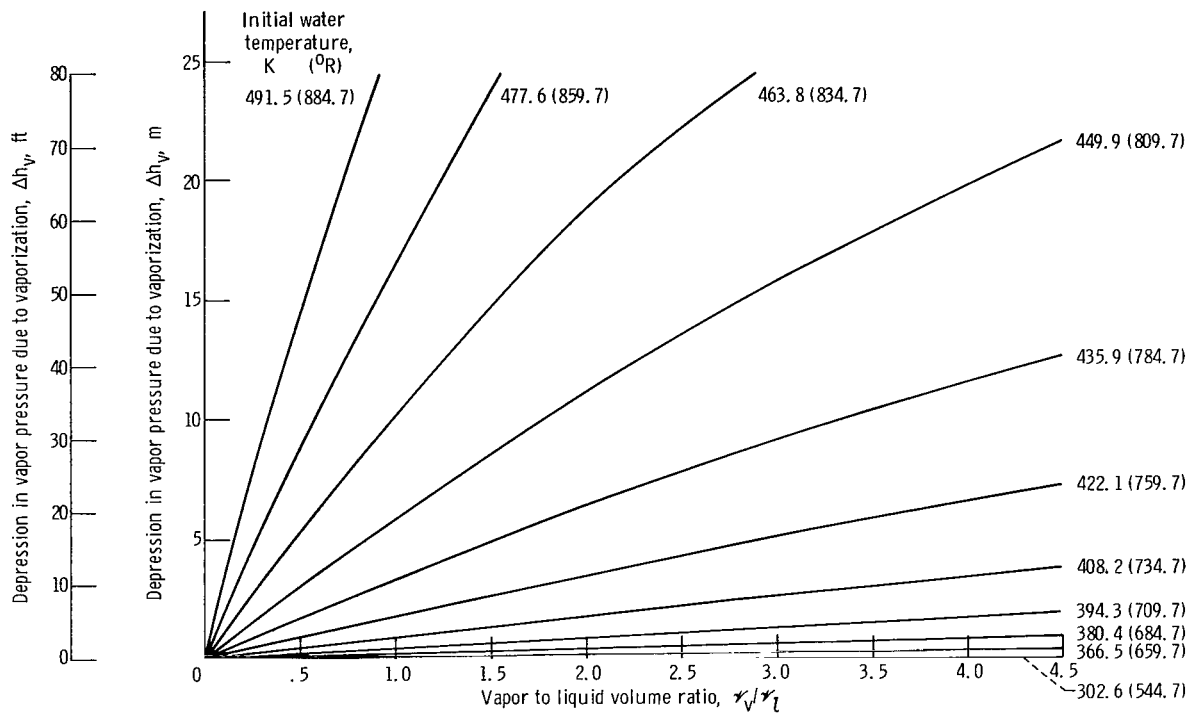


Figure 8. - Calculated vapor pressure depression due to vaporization as a function of volume ratio for several water temperatures.

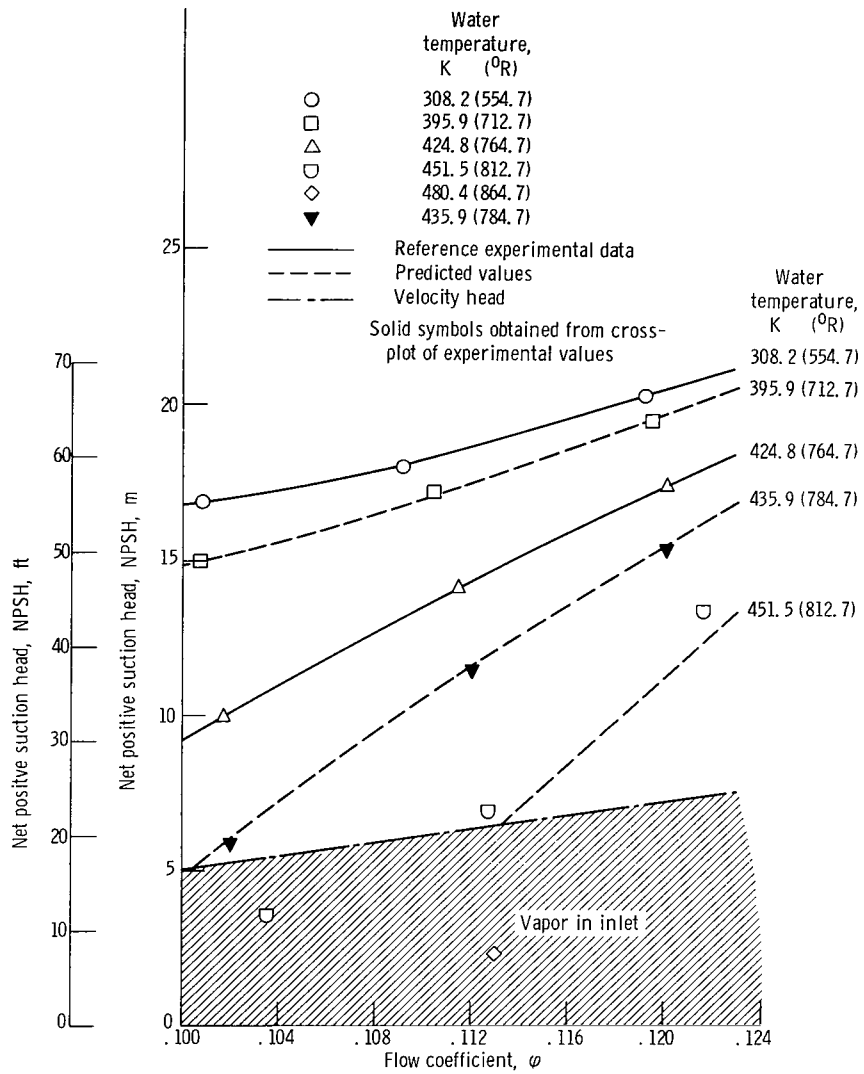


Figure 9. - Comparison of predicted and experimental values of net positive suction head for 80.6° helical inducer in water at head-rise coefficient ratio of 0.7 and rotative speed of 15 000 rpm.

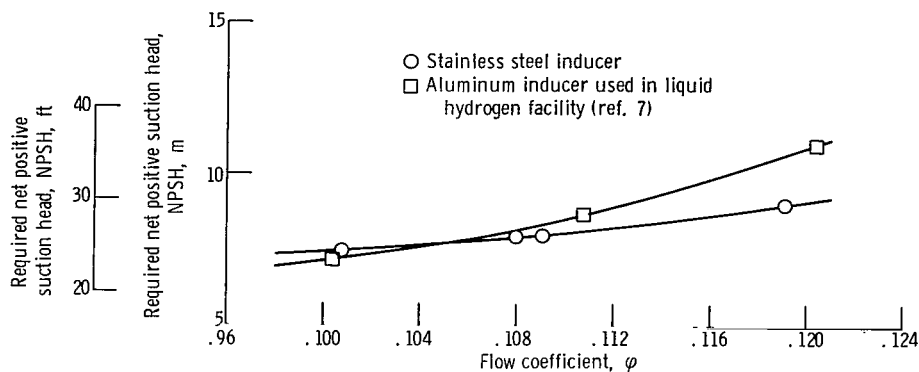


Figure 10. - Comparison of required net positive suction head for two 80.6° helical inducers in room temperature water at head-rise coefficient ratio of 0.7 and rotative speed of 10 000 rpm.

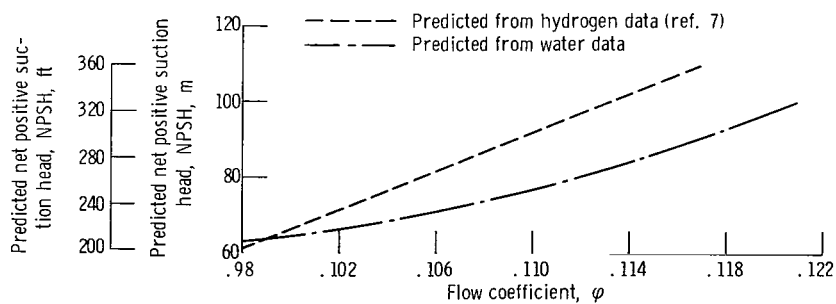


Figure 11. - Comparison of predicted net positive suction head for 80.6° helical inducer in hydrogen at head-rise coefficient ratio of 0.7, rotative speed of 30 000 rpm, and a hydrogen temperature of 13.8 K.



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